5. Thoughts on Becoming and Being an Analog Circuit Designer

Special commentary by Laurel Beth Joyce, Greg's wife

"My favorite programming language is solder."
—Todd K. Whitehurst
Stanford University, 1988

Well, here I am, finally writing this book chapter! Instead of trying to tell the reader how to design analog circuits (I'll leave it to the folks with circuits named after them to do that, unless you take my courses), I will discuss several aspects of becoming and being an analog circuit designer. I will try to cover a few areas that I think are important, particularly to someone considering a career in this field. My wife's comments near the end of this chapter will also be of considerable interest to the significant other (S.O.) of anyone considering this career choice.

Analog Circuit Designers

What type of person becomes an analog circuit designer? Perhaps the best way to address that question is to start by describing the types of people who do *not* become analog circuit designers! Examples are folks whose second career choice would have been accounting, people who say "dude" a lot, people who have time to sit around wondering why their belly-button lint is gray,[1] people who wear Birkenstock sandals and eat alfalfa, people who are frustrated by devices more complex than a paper clip, and people who are repeatedly abducted by space aliens.

In other words, analog circuit designers tend to be a creative, practical, and curious bunch of folks who are rarely abducted by space aliens. The typical analog designer doesn't worry too much about shaving on weekends (especially the female ones), drinks beer and eats pizza, owns an oscilloscope (see "Things You Need to Survive as a 'Real' Analog Designer" below), thinks modern art consisting of blank white canvases is a bunch of crap, occasionally uses "swear words," and may be considered a bit "eccentric" by his or her friends and colleagues. Over the years, knowing a fair number of analog designers, I have only encountered one notable exception: Jim Williams.[2]

1. Actually, my friends at the Office of Navel Research in Washington, DC, have studied this issue extensively. They have found that belly-button lint color is a complex function of clothing color, belly-button humidity, and the amount of cheese consumed.
2. He doesn't drink beer.

Why should anyone want to become an analog designer? Aside from the large amounts of money you earn, the hordes of attractive members of the opposite sex that are drawn to you by the heady smell of solder, the ability to simulate circuits in your head, and the undying respect of all other engineers, there is one really important advantage to this line of work: it's fun!

In fact, designing circuits can be absolutely wonderful. You create, from scratch, a complete working[3] circuit that accomplishes a function you (or your boss) desire. Once you get some experience, you can visualize how the circuit building blocks you know can be combined to get what you want. Sometimes you realize that you need to invent something really new to do a particular function. Creativity and a bit of insanity really helps with that.

You don't need big power tools, a yard full of old cars up on blocks, or a trip to the Himalayas to build analog circuits. Actually, what you do need are small power tools, a garage full of old oscilloscopes up on blocks, and a trip to some surplus stores in Mountain View. In any case, once you reach some level of "analog enlightenment," it is really addictive. This is good, because the majority of engineers have gotten so seduced by digital circuits and software that some very big electronics companies exist that do not have a single decent analog circuit designer in house. In other words, if you learn analog circuit design, you can get a job!

"I've heard enough! Sign me up!" If that's what you are thinking,[4] you may want to know how you can become an analog designer. One way is to learn "on the street" ("Hey buddy, wanna pick up some transistors cheap? . . . They've got high betas and they're clean!"). That works eventually (the word "eventually" is key), but most people go to a university and learn there. If you are remotely interested in the latter option, please read on . . .

Analog Boot Camp: One Way to Become an Analog Designer

I teach analog circuit design at Stanford,[5] along with my colleagues in the Department of Electrical Engineering. In recent years, we have taken great pains to upgrade the electronics courses to include more practical, design-oriented material. My own courses are considered "analog boot camp" for undergraduates who think of transistors only in

3. (eventually)
4. (if not, please put this book down and read that biography of Bill Gates over there to the left)
5. The opinions and/or other crap in this chapter are completely the fault of the author and do not reflect the opinions and/or other crap of Stanford University in any way.

terms of band diagrams. I'll share with you some of our "indoctrination" techniques . . . [6]

First, we administer an exam to weed out the people who should really be learning about French history or something like that. Here are a few sample questions:

Choose the single best answer.

1) The best all-around programming language is:

a) C
b) C++
c) BASIC
d) Fortran
e) solder

2) A "GUI" is:

a) a productivity-enhancing graphical user interface for modern computers
b) useful for opening beer bottles
c) a voltage regulation circuit invented by famous Dutch EE Cornelius von Fritzenfratz
d) who gives a crap, this test is about analog circuits!

3) Analog circuits are:

a) circuits involving only resistors and capacitors, like in first-year electronics, dude
b) circuits built with digital logic and no more than two discrete transistors that you debug by reprogramming EPROMS until they work
c) not needed now that we have the "Newton"
d) really cool

4) SPICE is:

a) stuff like salt and pepper you put on your food
b) the reason nobody needs to build real circuits at all
c) a program designed to see how quickly your computer bogs down when doing floating-point operations
d) the only reason we need computers, other than Tetris.™

5) "Solder suckers" are:

a) PG-rated, but can occasionally be seen on National Geographic specials
b) the black holes of circuits, often seen running around with current sources invented by Mr. Wilson (from "Dennis the Menace")
c) people who are lured into analog circuit design by evil professors
d) plastic pumps used to remove solder from component leads where those uneducated about analog design have made mistakes

6. These techniques have been developed over several decades by carefully selected teams of scientists from all over the world.

That sort of thing helps weed out the sick, the feeble-minded, and the history majors. Then we begin analog "basic training," which involves learning the following song for drill practice and considerable healthful marching and shouting.

Analog Boot Camp Drill Routine

by G. Kovacs

(The words are first barked out by the professor, then shouted back by students marching in formation.)

Analog circuits sure are fine,
Just can't get 'em off my mind.

Digital circuits ain't my kind,
Zeros and ones for simple minds.

I guess NAND gates aren't all that bad,
'Cause I need them for circuit CAD.

One, two, three, four,
Gain and bandwidth, we want more.

Five, six, seven, eight,
We don't want to oscillate.

Widlar, Wilson, Brokaw too,
They've got circuits, how 'bout you?

(*repeat*)

I also ask a few random questions and have been known to order a few push-ups here and there if, for example, a student cannot correctly distinguish between the Miller and Budweiser Effects. Now the students are ready for their plunge into the world of analog . . .

At this point, they are taught theory in one class and hands-on aspects in another. Essentially, the idea is to progress from the basic idea of an operational amplifier (op amp) through the necessary circuit building blocks that are required to design one. Finally, we reach the point where the students know enough to do that, and then we get into feedback and stability. Meanwhile, in the laboratory part of the class, the students are learning how to destroy most of the circuits covered in lecture. It is in the lab that we teach them the all-important "smoke principle" of solid-state devices. This is the formerly very closely guarded industrial secret that each discrete or integrated circuit is manufactured with a certain amount

of smoke pre-packaged inside. If, through an inadvertent wiring error, conditions arise through which the smoke is permitted to escape, the device ceases to function. We also train the students to recognize and distinguish the smells of different burning components ("Ah yes, a carbon resistor seems to have burned up in this circuit . . . smells like 220KΩ.").

I am not kidding about this, but not more than ⅓ of the EE students at this level have ever used a soldering iron before! In contrast, nearly all of them have driven a BMW and can explain leveraged buyouts in great detail (I presume this is a phenomenon more common at schools where yuppy pupae are present in large numbers). After a little trial and error, most of them learn which end of the soldering iron is hot (I am told that those who never really figure this out generally transfer to a local state-run university where they can just write software, but I have no concrete evidence of this). Pretty soon, they not only know how to solder, but also how to use a wide range of up-to-date test equipment. (I worry about the ones who keep looking for an "auto setup" button on a voltmeter, though! . . . more on this below.)

At this point, we get the students into the guts of Boot Camp: design it, SPICE it, make it work, and examine the differences between the SPICE model and the real thing. The idea is to teach simulation as "virtual instruments" and then introduce the real ones (the type with knobs). We provide SPICE decks[7] for each circuit that are already on the student computers. We leave out critical component values for the students to choose. They have to come to lab with a running simulation and then build the circuit. This can be fun to watch the first time, as the students look around the lab for 10,000 amp current sources, diodes with forward voltages of exactly 0.700V, and 13.4567E3 ohm resistors. Eventually, they figure things out and get things working.[8]

We ask them to simulate and build a lot of discrete circuits, including power supplies, basic op amp circuits, single-transistor amplifiers, a simple op amp built from discretes, and power amplifiers. After that they build a project of their own choosing, demonstrating their analog design skills. This exercise gives them a chance to construct a complete circuit from scratch and write an instruction manual, specification sheet, and marketing sheet for whatever it is. Some students have built really amazing things, such as a waveform synthesizer, a heterodyne spectrum analyzer, an infrared remote control system, an acoustic rangefinder, etc. Some have built devices that are also humorous, including a fake leopard

7. "Gee, Dad, why do they call them SPICE decks?"
"Well, son, way back before they found a practical use for the 'Newton' in 2027, computers used punched paper cards as a way to enter data and programs. We called a stack of those cards a 'deck'."

8. Our current sources only go to 9,000 amps, we keep the 0.700-V diodes in another room, and they need to specify resistor values to a few more decimals or our component supplier doesn't know which value to provide.

fur-covered[9] laser/galvanometer system for a light show, a guitar amplifier that "goes to eleven," and a contraption that the student proudly described as a "large vibrator" (he meant "multivibrator," but it was terribly funny at the time).

Does it work? Are we able to turn out decent analog designers? Well, it seems to be working, and feedback from companies who have hired our students is positive.[10] For me, success can be measured by the number of students who actually learn to love analog circuit design despite the fact that they are growing up in a world devoid of Heathkits and basements full of surplus electronics to hack circuits with.

To illustrate the transformations that occur, I have reproduced a letter home from one of the students on his first and last days in Boot Camp (the names have been changed to protect the student's identity):

Day 1 of Boot Camp:

Dear Mom,

Things are going fine here at Stanford! Today we learned about "operational amplifiers." They are triangle-shaped things that can do basically anything. The textbook says they have an "ideal voltage source" inside. Tell Pop that this means I can hook one up to power the whole farm when I get home this summer! I can't wait!

Love,
Billy

Last day of Boot Camp:

Dear Mom,

I just finished my analog circuit training at Stanford! I now know I was wrong about operational amplifiers being able to power the whole farm! That was totally silly, because they are simply integrated circuits, and thus require external power. Also, their non-zero output resistance and short-circuit protection circuitry means that they can only supply a few milliamps of current.

Do you know why smoke comes out of transistors when they get too hot? I will explain it all to you, Pop, and the farmhands when I get back there in a few weeks.

I think we should consider turning the barn into a circuit design laboratory. Bossie could stay in my room, since I will probably spend most of my time out there. Please let me know if this is OK, because I would rather do this than take a job doing software-

9. Of course, we use only fake leopard fur because it is an endangered species, and we are very politically correct. The only type of skin that is still OK to use for decorative purposes is that of Caucasian heterosexual males, but we were out of it at the time.
10. We all know that positive feedback can lead to oscillations, so we will have to keep an eye on this situation. Raising tuition seems to provide the necessary negative feedback to keep the system stable.

simulated power consumption validation of a subset of indirect-jump instructions of the new Valium computer chip at Interola's new lab in Lumbago, Oregon.

Love,
Billy

What Should Aspiring Analog Designers Read?

There is good stuff on analog circuits to read out there, and generally it is reasonably easy to locate. I am not going to go into the large number of books available other than to point out that you really need to have Horowitz and Hill, *The Art of Electronics* (Cambridge Press) and Gray and Meyer, *Analysis and Design of Analog Integrated Circuits* (John Wiley and Sons). Those two books are simply the essentials;[11] it's easy to supplement them from the droves of texts out there.

As far as journals go, there are several good ones out there. Of course, the IEEE has a few. Then there's *Wireless World*, put out by a bunch of hackers in the United Kingdom, with real depth mixed right in there with fun projects. Another good foreign offering is *Elektor*, which is put out by a bunch of hackers in Holland (the closed-loop cheese fondue controller project last year was awesome). The *Computer Applications Journal* (alias *Circuit Sewer*) is worth reading, but is aimed at those who think debugging a piece of hardware involves mainly fixing software (it is 90% digital subject matter, with occasional forays into scary things like op amps). What about those old standards like *Popular Electronics*? Well, they are OK for the occasional project idea, but as for technical content, I generally say, "Later!" (especially to ones with names like *Electronics Now!*).

One of the richest sources of information, and probably the least obvious to beginners, is the application notes written by the manufacturers of integrated circuits. Just think about it . . . they are trying to sell their wares by getting you excited about their uses.[12] They are absolutely packed with interesting circuits! Usually, you can get them for free, as well as sets of data books, just by calling the manufacturers. Saying you are a student usually helps, and will often get you free samples too. In case you don't know, the best ones are from National Semiconductor, Linear Technology, Maxim, Analog Devices, and Burr Brown.

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11. Did I mention that this book is also one of the essentials? In any case, you are already clever enough to be reading it, so why bother!
12. They have to accomplish this by showing you cool circuits you can build, as opposed to traditional marketing approaches, such as those used to sell beer. I am still waiting for the Swedish Bipolar Bikini Team, though!

Things You Need to Survive as a "Real" Analog Designer

I am occasionally asked what you need to survive as a "real" analog designer. Well, this is a highly personal matter, but I can at least give my standard answer, which is the things I need (in order of importance):

1. An understanding significant other (S.O.)
2. A laboratory dog to keep my feet warm
3. A basic supply of discrete and integrated components
4. A decent oscilloscope
5. A power supply
6. A soldering iron
7. Basic hand tools
8. Cheap beer
9. A pad and pencil

An understanding S.O. is critical, because when you start coming home with large chunks of blue-colored equipment and go misty-eyed when you see an old Tektronix catalog, it takes a special kind of person to understand! Analog designers tend to build up huge collections of old oscilloscopes, circuit boards, random metal boxes, and all sorts of "precious" items that will come in handy some day. I think meeting an analog designer who isn't a packrat is about as likely as meeting the Swedish Bipolar Bikini Team.

A typical workbench for analog circuit design is shown in Figure 5–1. In addition, the "analog workstation," where most of the really good circuit ideas are developed, is shown in Figure 5–2. The very useful labora-

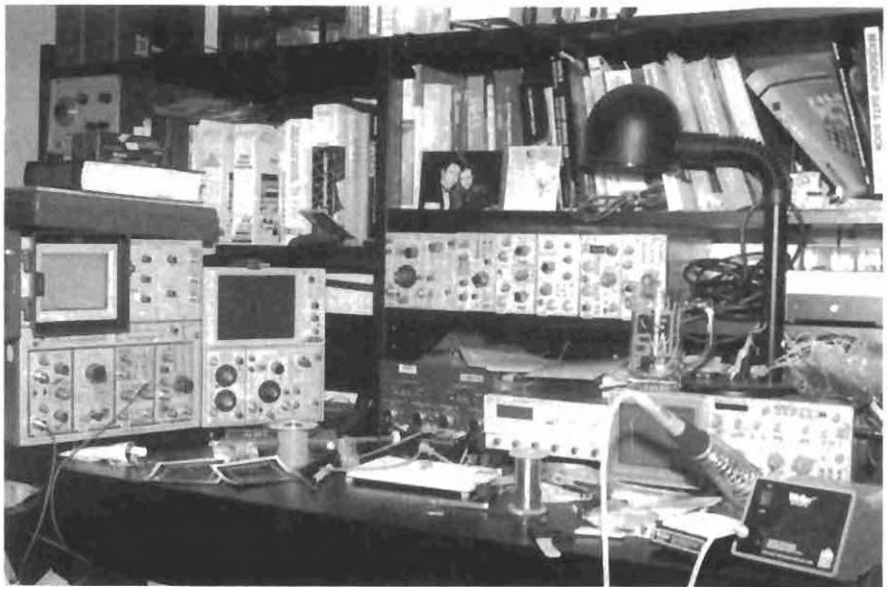

Figure 5–1. A typical workbench used for analog circuit design.

Figure 5–2.
An analog work station. This is the place many great circuit designs are developed.

tory dog (black Labrador called Rosie) is shown in Figure 5–3. She is better with a soldering iron than most engineers I know!

Comments on Test Instruments

Good test instruments are critical to a person's success as an analog circuit designer! They are the equivalents of musical instruments to a musician . . . you never share your Stradivarius (i.e., Tektronix 7904A oscilloscope) and need to be intimately familiar with its nuances to get the best performance out of it. Bottom lines here: 1) don't buy cheesy foreign test gear unless you absolutely have to, and 2) when you find

Figure 5–3.
Rosie, the laboratory dog in our house. She will debug any circuit for a piece of beef jerky.

your beautiful oscilloscope, spot-weld it to some part of your body so that it is not borrowed without your knowledge.

I am an absolute hard-core fan of Tektronix test equipment. Tektronix oscilloscopes (the most important item) are available with a wonderful user interface and provide extremely high performance plus real versatility. The only problem is that they don't make that kind any more.

In recent years, there has been a trend toward computer-controlled, menu-driven test instruments, rather than instruments that use a dedicated switch or knob for each function (so-called "knob-driven" instruments). In most cases, the push for menu-driven test instruments has an economic basis—they are simply cheaper to build or provide more features for the same price. However, there are practical drawbacks to that approach in many cases. A common example, familiar to anyone who has ever used an oscilloscope, is the frequent need to ground the input of a vertical channel to establish a "zero" reference. With a knob-driven instrument, a simple movement of the index finger and thumb will suffice. With a menu-driven instrument, one often has to fumble through several nested menus. This really sucks, and I think it is because they are starting to let MBAs design oscilloscopes. (I suppose one possible benefit of this is that soon 'scopes will have a built-in mode that tells you when to refinance your mortgage!)

Grounding a vertical channel's input is something you need to do often, and it is quite analogous to something familiar even to digital engineers, like going to the bathroom. You simply wouldn't want to scroll through a bunch of menus during your mad dash to the bathroom after the consumption of a bad burrito! There are several similar annoyances that can crop up when using menu-driven instruments (how about ten keystrokes to get a simple sine wave out of a signal generator?!).

To be fair, menu-driven instruments do have advantages. However, since I am not a big fan of them, I'll conveniently omit them here.[13] It always pisses me off to watch students hitting the "auto setup" button on the digital 'scopes in our teaching lab and assuming it is doing the right thing for them every time (not!). If we didn't force them to, most of them would not even explore the other functions![14] Advertisements for these new instruments often brag that they have a more "analog-like feel" (as opposed to what, a "primordial slime ooze feel"?). Let's get real here . . . at least in part, this is just another incarnation of the old engineering saying, "If you can't fix it, make it a feature." Since when was a "more chocolate-like taste" a real key reason to buy brown sludge instead of chocolate?

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13. One of the key advantages is that they can help us lure would-be engineers into the lab. The type of EE student who doesn't like hands-on hardware engineering (you know, the ones who end up working for Microsloth) can be attracted by the nice menus long enough to actually see how much fun electronics can be.
14. At this point, I will admit that our VCR does blink "12:00," but I hear there will be an "auto-setup" mode on new ones! I had to fiddle with it for hours to get it to blink "12:00"

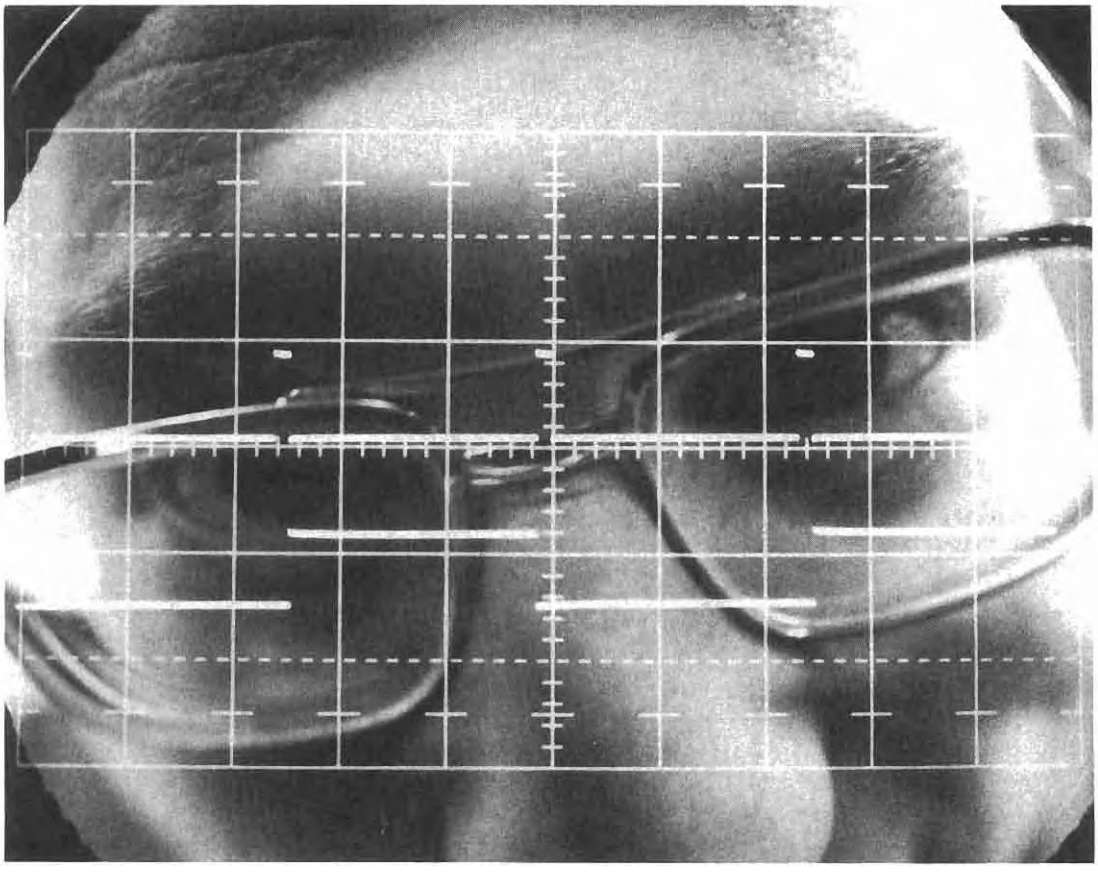

Figure 5–4.
What you look like to your oscilloscope (yuk!). Actually, this is what Jim Williams looks like to his oscilloscope. You probably won't look that silly.

I am sad to report that knob-driven analog test instruments are becoming more difficult to get. I also have to admit that performance is improving while relative prices are dropping, so "user-friendly" instruments aren't all that bad. Students take note: at least try to check out instruments with knobs, in between pressing "auto-setup" and "help" keys! A great place to find this stuff is at your friendly neighborhood university (we'll never surrender!), local "ham radio" swap meets, and companies that specialize in used test equipment. Also, remember to be nice to your oscilloscope! What you look like to that faithful piece of test gear is shown in Figure 5–4.

What Does My Wife Think about All of This?

This section was written by my wife, Laurel Beth Joyce, the pride of Mars, PA.[15] It is added to provide an extra sense of realism and to prepare

15. I am not making this up. This is because I don't need to. Western PA has tons of great names of towns, like Beaver, Moon, etc., as well as great names for public utilities, like "Peoples' Natural Gas." Naturally, nobody from there thinks any of this is funny.

a would-be analog circuit designer for the impact this career choice has on one's home life.[16]

If your S.O. is an analog designer, your relationship will be much happier once you come to understand and accept some of the basic differences between analog circuit designers and normal people.

1. Analog circuit designers consider beer one of the major food groups and an essential hacking tool. (See "Things You Need to Survive as a 'Real' Analog Designer.") To avoid major altercations, be sure there's always beer in the house.

Fortunately, my husband's students signed him up for a Beer-of-the Month club. Each month the UPS lady drops a big box of beer on our doorstep, putting him in hacker heaven and saving me many trips to the beer store.

2. Circuit designers don't tell time in the same way that the rest of us do. Unfortunately, I still haven't figured out the exact formula for converting circuit design time into regular time.

For example, let's say my husband is in the middle of a hacking project at work and he calls to tell me that he's going to head home in about half an hour. If he's alone and I know he's working on a project that doesn't require an oscilloscope, I simply multiply the time by two. If there is an oscilloscope involved, I multiply by three. If he's got any circuit design friends with him, I generally add at least 40 minutes per friend if they're not drinking beer and an extra 2 hours per friend if they are. I believe the beer effect is nonlinear. My current empirical formula for computing circuit design time in minutes is thus:

$$t_{cd} = (2 + N_{scopes})\, t + (40 + 120\, k_{brewski})\, N_{friends}$$

where N_{scopes} is the number of oscilloscopes present, $k_{brewski}$ is the linear approximation for the nonlinear beer effect (taken to be one, but can be replaced by a suitable time-dependent nonlinearity) and $N_{friends}$ is the number of circuit design friends present.

My calculations are rarely perfect, so I'm pretty sure there are some other variables involved. It may have something to do with the number of op amps in the project, but since I'm still trying to figure out what an op amp is, I haven't quite determined how that should factor into the formula.

My suspicion is that this formula varies slightly among hackers, but you're probably safe to use this as a starting point for deriving your own formula.

3. Circuit designers have an interesting concept of economics. Last weekend we wandered down the breakfast cereal aisle of our local

16. The opinions and/or other crap written by my wife are completely her fault and do not reflect the opinions and/or other crap of Stanford University or myself in any way.

grocery and my husband was astounded that the big box of Cap'n Crunch cost $4.58. He considered it so expensive, he wanted to put it back on the shelf.

In contrast, he tells me that $2,000 is a bargain for a 20-year-old, used oscilloscope that only smokes a little bit and will only require one or two weekends to fix up. And $1,000 is a great deal on a 'scope that doesn't work at all, because it can be cannibalized for parts to repair the 'scopes that smoke comes out of (assuming that it has enough parts left that never smoked).

4. When an analog circuit designer brings home a new piece of equipment, the S.O. becomes invisible for several hours.

I used to get jealous every time a new 'scope or signal generator came into the house. He'd burst in the door all breathless and say, "Hi, Laurel, look what I found today. Isn't she beautiful? I'm just going to take her upstairs for a few minutes." The two would disappear into the lab and I'd hear lots of cooing and giddy chatter that went on until daybreak. It was as if my S.O. was bringing home his mistress and dashing up to our bedroom right under my nose.

If the dog or I went into the room, he wouldn't even notice us. I could tell him that beer had just been outlawed in the United States or the dog could vomit on his shoes. He'd just say, "I'll be with you in a minute," and go back to grinning and twiddling the knobs of his new toy.

When you realize it's no use being jealous and that you'll never be able to compete with these machines (unless you want to turn to the folks at Tektronix for fashion advice and get some clothes in that particular shade of blue, some 'scope knob earrings and some WD-40 cologne), you can actually have some fun when your S.O. is in this condition. If you like to watch TV, you've got the remote control to yourself for a few hours. If you have friends that your S.O. can't stand, invite them over for a party. If you're angry with your S.O. you can stand there and say nasty things ("You solder-sucking slimeball!"), get all the anger out of your system, and he'll remain totally oblivious. Be creative!

I was miserable before I learned that these basic differences and quirks are characteristic of *most* analog circuit designers, not just my husband. When I finally understood that they're simply a different species, my bills for psychoanalysis decreased significantly.

There are a couple of other things that help, too. First, ask all of your relatives to move to towns where there are used test equipment shops or frequent swap meets. If you don't, you may never see them again. It took six years for my husband to meet my Aunt Gertrude, but as soon as he found out that Crazy Egbert's World of 'Scopes was only 12 miles from her house, we were on an airplane—"Because I feel terrible that it has taken me so long to meet your aunt"—within 24 hours.

And, when all else fails, you may have to resort to the spouse alignment unit (SAU). Mine is a wooden rolling pin (shown in Figure 5–5),

Figure 5–5. The pride of Mars, PA, with her spouse alignment unit (SAU).

but I hear a baseball bat or cast-iron skillet works just as well. The SAU comes in handy, for example, when you're hosting a large dinner party, all the guests have arrived and are waiting for their meal, and your analog circuit designer has said he'll join the party "in just a minute" for the past two hours. In this situation you should quietly hide the SAU up your sleeve, excuse yourself while flashing a charming smile at your guests, waltz into the lab, yank the plug on the soldering iron and strike a threatening pose with the SAU.

It's kind of like training a dog with a rolled-up newspaper—you only have to use it once. After that, the sight of the unit or the threat that you're in the mood to do some baking will yield the desired response.

Conclusion

I hope this chapter has given you some sense of what you need to learn and obtain to become an analog circuit designer, as well as some of the emotional challenges in store for you. It would be great if you considered it as an alternative to the digital- or software-based engineering drudgery that you are statistically likely to end up doing. There may yet be some burnt resistors and oscillations in your future!